Novel Approach to Modelling the Elastic Waves in a Cluster of 3D Fractured Structures

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Summary

This work presents the results of modelling the cluster of 3D vertical fractures in the heterogeneous medium based on the 3D SEG/EAGE Overthrust model. In the previous work, we considered the approach to modelling 2D fractures based on the model of a two-shore extremely thin fracture. The results showed the effectiveness of the developed method to modeling the elastic wave propagation in fractured geological media. In this work, a similar approach to modelling a cluster of 3D vertical fractures is presented. The wave fields and the synthetic seismograms for the models with and without fractured zone are analyzed. The results demonstrate the significant contribution of fractures into the observed wave field.

Introduction

Numerical modelling of seismic wave propagation in complex geological structures can be used in different geophysical applications, including mineral exploration, hydrocarbon (HC) reservoir monitoring, and environmental study. Geological formations often contain different heterogeneities, such as fractures (Leviant et al., 2019). It is necessary to consider fractures in mathematical models of seismic wave phenomena and analyze the observed seismic data accordingly.

This paper presents the results of numerical modelling the seismic waves spreading in heterogeneous geological medium with fractures for the 3D case. The main model is based on the well-known 3D SEG/EAGE Overthrust model (Aminzadeh et al., 1997). The Overthrust model is an onshore velocity model with complex geological structure. This realistic model and the corresponding synthetic data are widely used in many publications (e.g., Operto et al., 2003, Sun et al., 2019).

In the previous work (Stognii et al., 2019), we considered the approach to modelling 2D fractures using the model of a two-shore extremely thin fracture. We analyzed the influence of the fracture angle inclination on the computational errors. The fractures parallel to the boundaries of the modelling grid produced the smallest computational errors. In addition, we extended the considered approach to modelling a cluster of several fractures. The results of numerical study demonstrated the effectiveness of the developed method to modelling the elastic wave propagation in geological media with fractured zone.

In this work, we extend this approach to modelling a cluster of 3D vertical fractures, based on the model of a two-shore extremely thin fracture (Khokhlov et al., 2020). The results of modelling the seismic response in the heterogeneous medium based on the Overthrust model with and without the fractures show significant differences. The synthetic seismograms demonstrate a remarkable contribution of fractures into the observed wave field, which has to be considered in analysis of seismic data.

Method and Theory

We use a system of linear elastic equations for describing the propagation of seismic waves in a heterogeneous medium:

$$\rho \frac{\partial V}{\partial t} = (\nabla \cdot T)^T \ , \tag{1}$$

$$\frac{\partial T}{\partial t} = \lambda(\nabla \cdot V)\, I \ + \ \mu\, (\nabla \times \ V \ + (\nabla \cdot V)^T\,) \ , \tag{2}$$

where $\boldsymbol{V}$ is the velocity, $\boldsymbol{T}$ is the Cauchy stress tensor, ρ is the density of the medium, t is time, λ and μ are the Lame parameters.

The fractures were modeled by a set of two-shore extremely thin fractures (Favorskaya et al., 2018, Khokhlov et al., 2019). The free slip condition was set on the boundaries of a fracture:

$$V_n^l = V_n^r \ , \tag{3}$$

$$T_n^l = T_n^r \ , \tag{4}$$

$$T_\tau^l = T_\tau^r = 0 \ . \tag{5}$$

Equation (3) means the equality of the normal components of velocity on both boundaries of a fracture. Equation (4) represents the equality of the normal components of the stress tensor, and equation (5) corresponds to zero tangential components of the stress tensor on the boundaries of a fracture.

We computed the wave fields in the models using the grid-characteristic method of the third order of accuracy (Muratov et al., 2018, Trangenstein, 2009). The contact conditions between different layers were calculated with the help of the transparent method.

The non-reflecting boundary conditions were set on the side boundaries of the model and on the bottom, while the free-boundary condition was established on the upper boundary.

Results

We carried out the computations of the wave field for the models with and without the fractures. The height of the model was 4.65 km, the width and length were 20 km and 20 km, accordingly. Fig. 1 presents a schematic view of the model. The color bar denotes the values of the longitudinal velocity. Fig. 2 depicts a schematic representation of the model with fractured structures. The size of a single fracture was 200 x 200 m^2 . The fractures were situated at a depth of 2 km in the center of the computational grid.

The point source of Reiker impulse was set in the center of the computational grid on the surface of the medium. The central frequency of the seismic source was 10 Hz as the full waveform inversion is usually carried out using the low frequencies. The receivers were situated on the surface of the medium with the 50 x 50 m steps in the x and y directions.

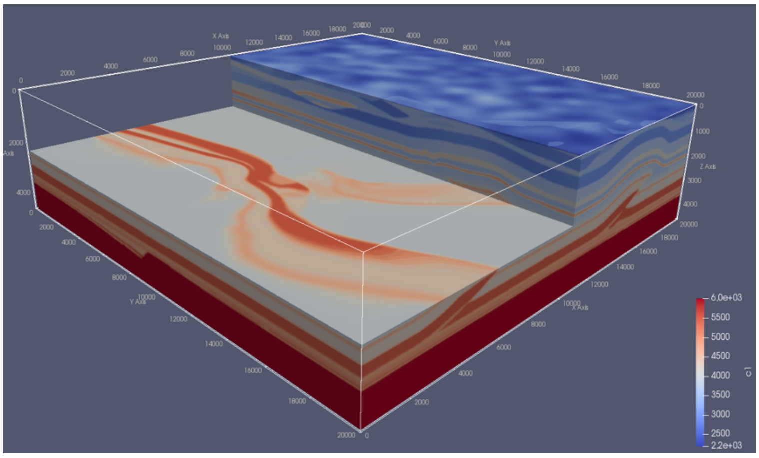


Figure 1 *Schematic representation of the model without fractures.*

First, we computer simulated the seismic waves in heterogeneous medium without fractures (Fig. 1). Then, we calculated the wave field in the heterogeneous medium with 200 vertical extremely thin fractures (Fig. 2).

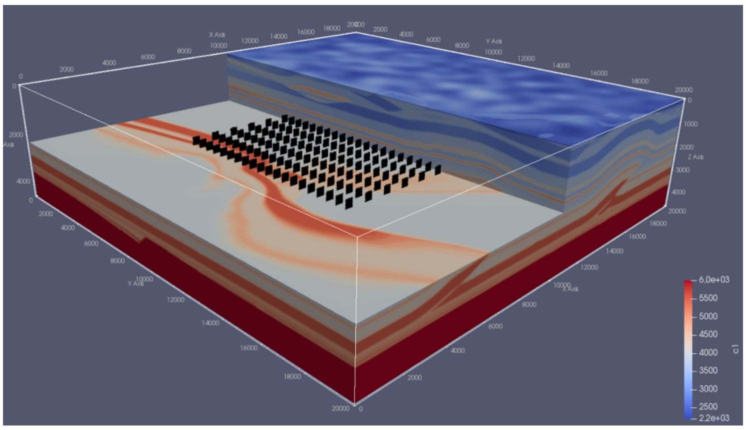
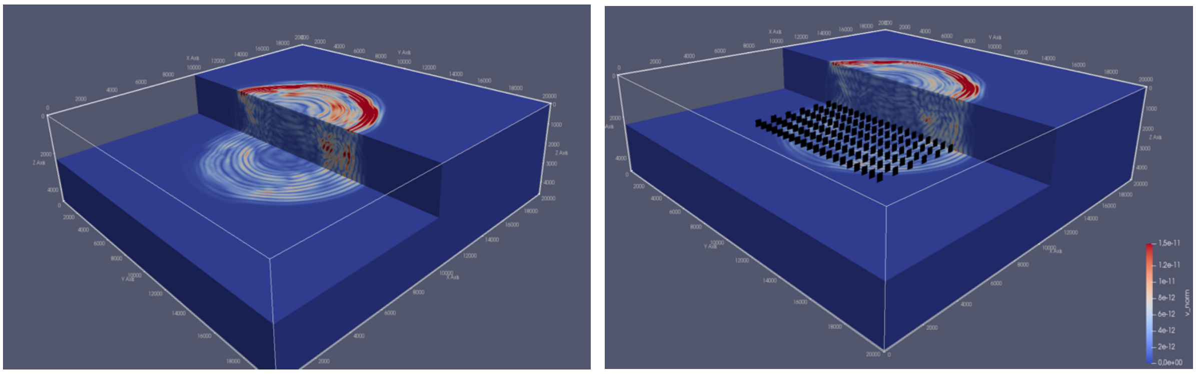


Figure 2 *Schematic representation of the model with the fractures.*

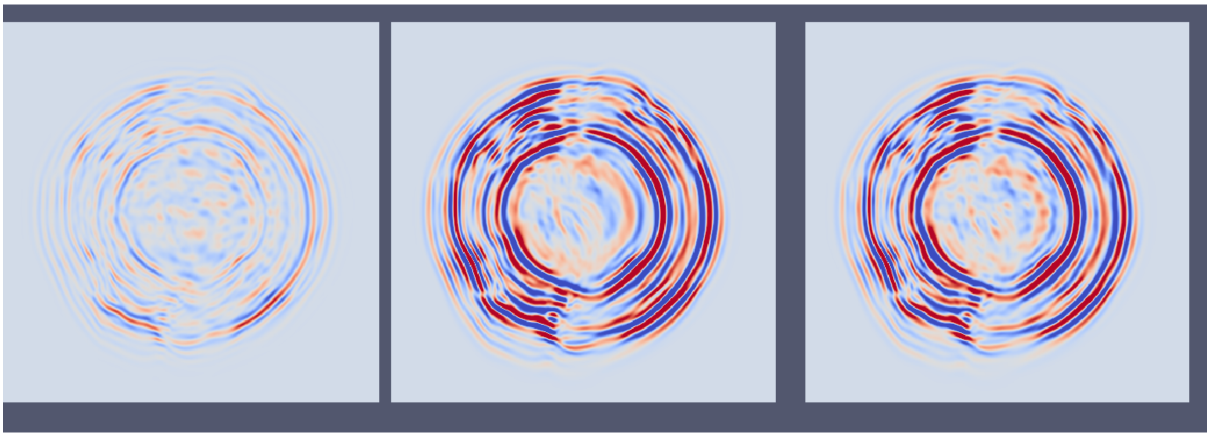
The wave fields for the models without and with the fractures at the same time moment 2 s are presented in Fig. 3. The color bar depicts the absolute value of the wave field.



a) the wave field in the model without fractures *b) the wave field in the model with fractures*

Figure 3 *The wave field distribution for the models without (a) and with the cluster of fractures (b) at the same moment of time equal to 2 s.*

The seismograms for the models with and without fractures are shown in Fig. 4. The pictures in Fig. 4 reflect the values for the vertical field components V_z in the receivers distributed over the XY plane on the surface ($Z = 0$) at the same moment of time equal to 2.4 s. The leftmost picture in Fig. 4 shows the anomalous wave field from the cluster of fractures. The middle picture shows the wave field for the model without fractures. The rightmost picture presents the overall wave field for the model with the cluster of vertical fractures. The color scale is the same for all the pictures in Fig. 4.



a) the anomalous field from the fractures *b) the total field in the model without fractures* *c) the total field in the model with fractures*

Figure 4 *The vertical field component (V_z) in the receivers at time moment of 2.4 s for different models: a) the anomalous field from the fractures, b) the total field for the model without fractures, c) the total field for the model with fractures.*

The last figure shows that the response from the fractured structures is smaller than the value of the total response, but it is still quite noticeable. This result illustrates a possibility of reconstructing a response from the fractured structures with the help of full waveform seismic modelling and inversion.

Conclusions

In this paper, we present the results of numerical modelling of the seismic wave propagation in the heterogeneous medium based on the 3D SEG/EAGE Overthrust model with a presence of a fractured zone. The grid-characteristic method of the third order of accuracy was used in all computations.

The wave field computer simulated in the model with the fractured structures was compared to the same field generated for the model without the fractures. The modelling results show that the wave field in the model with the fractured structures differs significantly from that in the model without the fractures. This result opens a possibility of locating a cluster zone based on seismic data. The future research will be aimed at reconstructing the fractured structures using the full waveform inversion.

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